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STUDIES OF RADAR-DEPICTED PRECIPITATION LINES

by

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FOREWORD

This report was initiated by the Illinois State Water Survey in Urbana, Illinois. The research work was accomplished with Illinois State Water Survey funds and by personnel under the general supervision of Glenn E. Stout, Head of the Meteorology Section, and under the general direction of William C. Ackermann, Chief of the Survey. A major portion of the radar data was collected under contracts DA-36-039 SC-42446 and DA-36-039 SC-64723 sponsored by the U. S. Army Signal Research and Development Laboratory.

The authors, Stanley A. Changnon, Jr. and Floyd A. Huff, were in charge of the research program for radar climatology. Included among those who assisted in the research were Richard G. Semonin, Thomas A. Prickett, Dorothy Hiatt, and Richard Barribal.

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ABSTRACT

This report consists of three separate studies; (1) a radar climatological description of precipitation lines as displayed by the CPS-9, (2) a similar investigation using the APS-15, and (3) the radar characteristics of precipitation lines associated with heavy rainstorms. These investigations were made to supplement the limited knowledge available concerning precipitation lines, with particular attention to severe weather phenomena and heavy rainstorms. Data are presented to describe rainfall line characteristics such as movement, orientation, duration, size, and growth tendencies. It was found that severe weather and heavy rainfall lines were larger, persisted longer, moved faster, and rotated more than other lines.

STUDIES OF RADAR-DEPICTED PRECIPITATION LINES

INTRODUCTION

To obtain information on the radar properties and the behavior of precipitation lines, climatological studies of lines depicted on CPS-9 and APS-15 3-cm radar sets located in central Illinois were performed,, Results of certain phases of these studies have been reported on elsewhere.[1,2] Studies of the precipitation associated with various synoptic conditions indicate that the most of the warm season precipitation in central Illinois is associated with precipitation lines.[3] Occasionally, these lines are responsible for severe weather and frequently they produce excessive rainfall. Therefore, investigations were made to obtain as much information as possible concerning precipitation lines, including their orientation, direction of movement, type of movement, speed, dimensions, growth tendencies, duration, time of occurrence, region of first detection, seasonal distribution, areal distribution, and association with severe weather conditions,, Average, median, and extreme values of these properties were computed for the lines, based on the mean values determined for each line during its duration.

This report incorporates the results obtained from three separate studies of line data. The first portion of this report is concerned with the results of a detailed climatological study of 196 precipitation lines depicted on a CPS-9 radar set.[1] Data used in this study were collected in the August 1954 through July

1955 period. The second study pertains to a similar climatological investigation utilizing data obtained from a low-powered APS-15 radar set. Measurements of 63 lines portrayed by this radar were made from data collected in the May through September 1953 and the March through September 1954 periods. The third part of this report summarizes an investigation of the characteristics of 106 lines associated with heavy rainfall in Illinois. GPS-9 radar data and hourly rainfall data from recording rain gages in Illinois were used in this study. Lines producing heavy rainfall, defined as hourly amounts exceeding one inch, were determined from data for the period from August 1955 through September 1958.

In any type of radar climatological study, the results should be classified according to statistical reliability for climatological purposes. Certain aspects of any rainfall pattern depicted by radar suffer from limitations such as attenuation and lack of infinite range, which are inherent features in all radar-rainfall measurements. Range-height losses, those losses in rain detection because rain cells are at ranges sufficiently distant to be below the radar beam, also limit radar detection of rainfall. Nevertheless, measurements were made with the understanding that certain results, especially those concerning time of occurrence, duration, location of line origin, growth, and dimensions, would indicate orders of magnitude. Data concerning orientation, speed, type of movement, and direction of movement are considered to be more reliable climatological statistics.

DESCRIPTION AND SOURCE OF DATA

Data used in this report consisted of 35-mm photographs of the PPI presentation of the high-powered, 3-cm, CPS-9 radar set and the low-powered, 3-cm, APS-15. Scope photographs from both sets were available for several reduced sensitivity settings of the radar receiver, but only data based on the maximum receiver sensitivity settings were used in recording line data. Both radar sets were located on a 50-foot tower at the University of Illinois airport, which is located in east-central Illinois about 120 miles south of ChicagO. Most of the surrounding terrain over which the radars scanned is relatively flat farm land affording relatively few obstacles to the radar beam. Additional data used in the heavy rainfall study included hourly rainfall tabulations from 85 U. S. Weather Bureau recording rain gage stations in Illinois and four concentrated networks containing 94 recording gages operated by the Illinois State Water Survey.

ANALYTICAL PROCEDURES

Measurements of the lines were made on a film viewer using a fixed transparent overlay with nautical-mile references to standardize all measurements. Once a line was determined, it was studied from the time of its initial appearance on the scope until its last appearance. No line was used in the analysis unless its radar history was observed from inception to dissipation. Information was recorded every 30 minutes; and for each half-hour measurement, the time, line width, line length, line orientation, azimuth and range from the radar station to the line center, distance moved by the line center and end points, direction of movement, and growth tendency were recorded,, For each line, all measurements of orientation, range, length, width, direction of movement, and speed were averaged, and the resulting means were used to describe these particular properties of each line.

The definition of a radar-indicated line was determined largely from examination of the scope appearances of many known squall lines. For one large echo or a group of echoes to be classified as a line, the echo presentation had to have a rectilinear appearance with a length of 50 miles or more. To define a line from a group of small echoes, four echoes had to be present within the minimum distance of 50 miles with not more than 10 miles between any two echoes© The echoes also had to have sharply defined outlines, especially on the leading edge. The behavior of the echoes was compared to see if similar characteristics of echo movement and speed were present. Two lines were considered as separate lines if separated by a distance of 25 miles or more; however, this distance could be less if prior development of the lines revealed a distinct separation in formation. If two lines moved within 15 miles of each other and the angular difference of the orientations of their major axes was 30 degrees or less, they were considered to be one line. At such times the less intense and smaller line was considered to be terminated.

GPS-9 CLIMATOLOGICAL STUDY

Introduction

The climatological study of lines depicted on the GPS-9 radar set was performed with data obtained from 264 days of radar operations during a 348-day period from August 7, 1954 to July 22, 1955. During this period, scope photographs of 320 lines were made, and records suitable for analysis were available for 196 of these lines. Most of the 196 lines were considered to be squall lines based on the definition that squall lines are lines of thunderstorms.[4,5] Seventy per cent of all lines were associated with thunderstorms, although in the spring and summer months 91 per cent of the lines could be considered squall lines because of their association with thunderstorms.

In addition to the basic climatological study of GPS-9 lines, two detailed investigations of line types were performed. First, data from pivoting lines, those rotating more than 10 degrees during their scope duration, were compared with data from nonpivoting lines. Nonpivoting lines are defined as those lines in which rotation did not exceed 10 degrees during their duration. Furthermore, data from the pivoting lines rotating in different directions were compared.

Data derived from lines associated with damage-producing severe weather were compared with line data derived for all lines to ascertain whether any pertinent differences existed between severe weather lines and others,, It was found that 34, or 17 per cent, of the 196 lines were associated with damage-producing severe weather.

Description of Data and Analytical Procedures

Data used in this study consisted of 35-mm photographs of the PPI presentation of the high-powered CPS-9 when operating on maximum receiver sensitivity. The maximum receiver sensitivity remained fairly constant during the 11-month period under study with an average sensitivity of -93 dbm. The scope photographs used were those made when the radar was operating on ranges from 150 to 400 miles,,

Results obtained from this study cannot be considered representative of an all-inclusive CPS-9 climatological study of lines for several reasons. Operations of the radar were not continuous from day to day during the 11-month study period; thus, the available data do not represent a complete sampling of all lines,, Eadar data were available for 264 of the 348 days in the study period, or approximately 75 per cent of the total days. Host of the non-operating periods were days when no precipitation was occurring within the range of the radar. Most of the data were collected between the hours of 0600 and 2300 CST. In addition, radar operations occasionally were terminated before a line disappeared from the scope, and the range often was reduced to collect certain types of data for contract purposes.(6) These factors made it impossible to continue measuring lines which had been present before the range was reduced or operations terminated. Consequently, incomplete echo line histories were found for 124 lines of the 320 lines detected in the 11-month period, and data on these 124 lines were discarded from the analysis. The analyses were based largely upon data from the remaining 196 precipitation lines with complete records. The data on severe weather associated with the lines were obtained from the U. S. Weather Bureau records.[7]

In addition to the above-described factors limiting climatological accuracy of the results, a 1-year record of any weather event cannot be expected to furnish a representative climatological sample. However, areal precipitation within radar range for the period of operation was only 0.15 inch above normal, suggesting that a near-normal sample of line data may have been obtained.

Climatological Findings

Orientation. The mean orientation of a line recorded was an azimuth in the 180-degree sector from south to north through west. The orientation of a line was considered to be the orientation of the major axis of the line, which is easily determined. Since many of the lines were rotating during their existence, an average orientation was determined for their scope duration, and this average value was used in determining the statistics for orientation. The median of the 196 average line orientations was 255 degrees, and 45 per cent of the lines had orientations ranging from 200 to 260 degrees. The orientations were sorted into 20-degree sectors to examine the frequency distributions, and the results are shown in Figure 1. The preferred 20-degree sector was from 220 degrees to 240 degrees.

Direction of movement. The direction of movement listed for each line was the one from which the line moved, expressed in azimuth. Since lines were found to have moved from many directions, a frequency distribution of movements was obtained by sorting

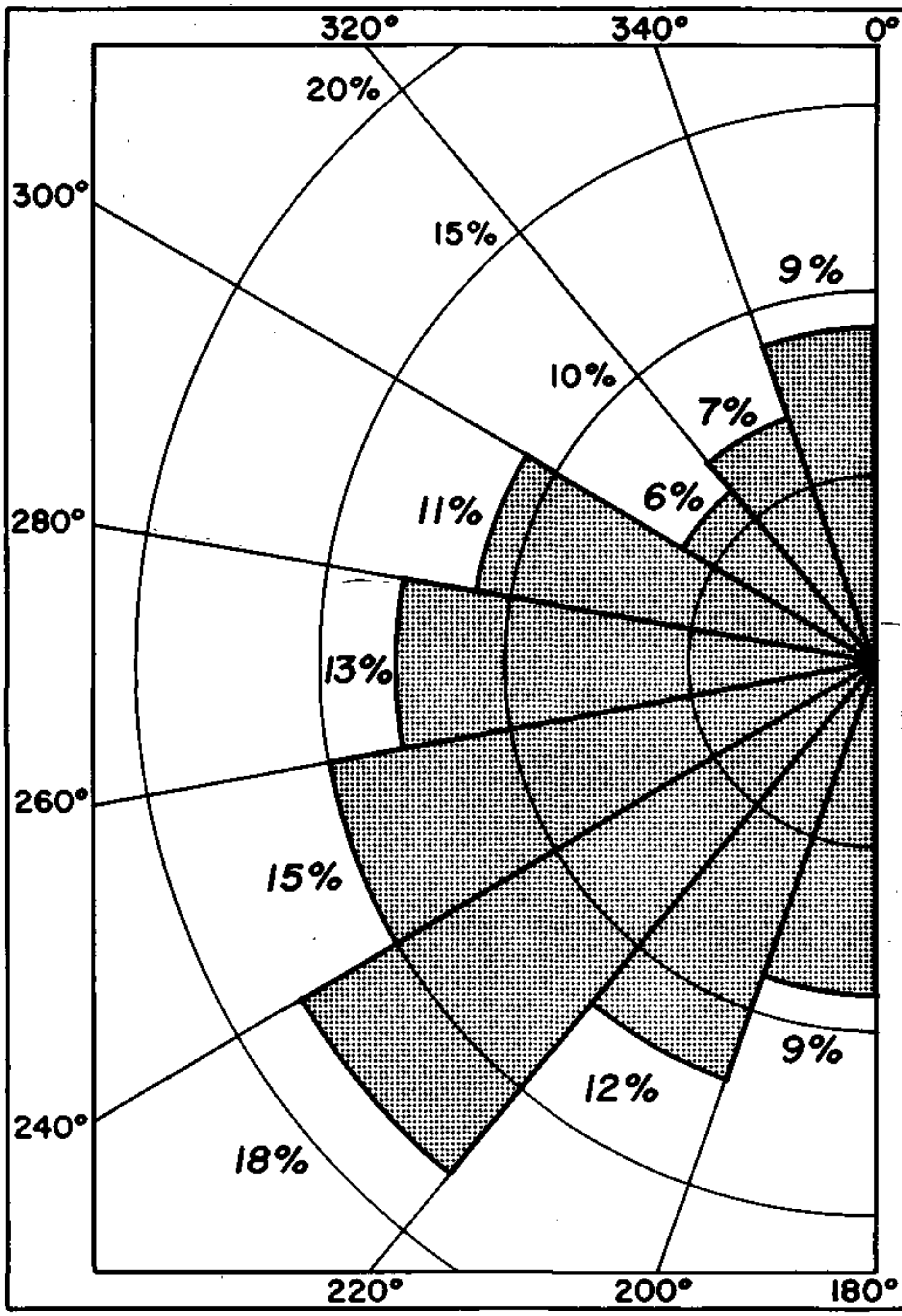


FIG. I DISTRIBUTION OF LINE ORIENTATIONS, CPS-9. FREQUENCY IN EACH 20° SECTOR EXPRESSED AS A PERCENT OF TOTAL LINES.

directions into the twelve 30-degree sectors of the compass. The frequency of lines in each of these sectors is displayed in Figure 2. Examination of this figure reveals that 37 per cent of the lines moved from azimuths ranging from 220 degrees to 280 degrees, and that a secondary maximum occurs in the sector from 310 to 340 degrees. The median direction of movement for the lines was 265 degrees.

TABLE 1

TOTAL AMOUNT OF PIVOTING DURING LINE DURATION

Degrees rotation	Number of Lines: Clockwise pivoting	Counter-clockwise pivoting	Non pivoting	Total	Lines with severe weather
0- 3.9	0	0	54	54	3
4- 7.9	0	0	31	31	6
8-11.9	6	4	20	30	3
12-15.9	10	13	0	23	1
16-19.9	6	3	0	9	6
20-23.9	7	7	0	14	4
24-27.9	3	8	0	11	3
28-31.9	3	4	0	7	0
32-35.9	1	4	0	5	2
36-39.9	2	2	0	4	2
≥ 40	2	6	0	8	4
Mean	21°	25°	4°	13°	22°
Median	18°	23°	3°	9°	18°
Greatest	60°	67°	10°	67°	67°
Least	11°	11°	0°	0°	0°

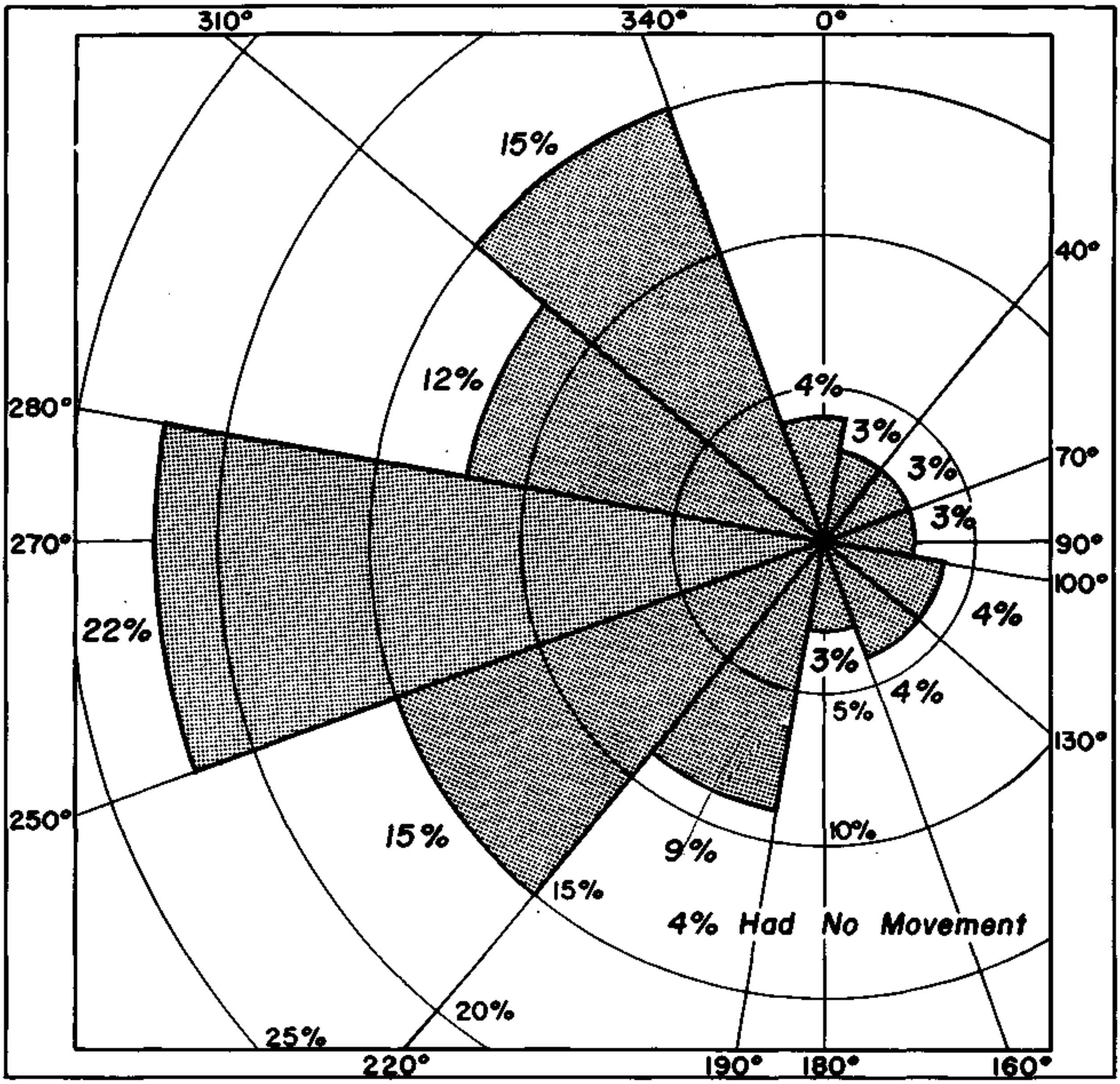


FIG. 2 DIRECTION OF LINE MOVEMENTS, CPS-9.
FREQUENCY IN EACH 30° SECTOR EXPRESSED AS PERCENT OF TOTAL LINES.

TABLE 2

AVERAGE AMOUNT OF PIVOTING PER HOUR

	Number of Lines				
Degrees rotation per hour	Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
0- 1.9	1	1	53	55	9
2- 3.9	7	6	22	35	6
4- 5.9	9	10	19	38	9
6- 7.9	5	6	6	17	3
8- 9.9	6	4	5	15	1
10-11.9	4	8	0	12	2
12-13.9	1	2	0	3	1
14-15.9	1	4	0	5	0
≥ 16	6	10	0	16	3
Mean	9°	10°	2°	6°	6°
Median	7°	8°	2°	4°	5°
Greatest	35°	31°	9°	35°	27°
Least	1°	2°	0°	0°	0°

Type of movement. Analysis of line movements indicated that most lines pivoted while they appeared on the scope,, Whether this rotation was produced by changes in speed,[4] direction of movement,[5] growth, or by a combination of these factors is unknown. Regardless of the reasons, the major axis of 96 per cent of the 196 lines exhibited a measurable amount of pivoting, and 91 of the lines (46%) had more than 10 degrees of rotation during their scope durations. As mentioned previously, lines rotating more than 10 degrees during their duration were classified as pivoting lines. As shown in Table 1, the median amount of pivoting for all 196 lines was 9 degrees during the entire line duration. The total amount of pivoting sorted by 4-degree intervals for the 196 lines is also shown in Table 1.

A median of 7 to 8 degrees of rotation per hour was obtained for the 91 pivoting lines compared to 4 degrees per hour for the entire sample of 196 lines (Table 2). Forty of the 91 pivoting lines rotated in a clockwise direction whereas 51 rotated in a counterclockwise direction. The maximum amount of line pivoting on the seope was 67 degrees (Table 1), and the maximum rotation per hour was 35 degrees (Table 2), These aspects of line movement were investigated further, and the results are presented in another portion of this reporto

Speed of movement. The median speed of movement for the center points of the leading edge of the lines was 24 knots. This speed is considered to be representative of the line speed. The mean speed of 27 knots (Table 3) is somewhat faster than had been expressed in another radar study[7] which stated that the mean speed of squall lines in the Middle West was 18 knots based on a sample of 20 lines. Radar attenuation and range-height losses produce errors in line speed calcualtions although these errors are considered to be relatively small. Fifty per cent of all lines had average speeds in the range from 16 to 35 knots. Only 12 per cent of the lines had average speeds greater than 45 knots, and 13 per cent had average speeds less than 11 knots, A sorting of average line speeds by intervals of 5 knots is presented in Table 3.

TABLE 3

AVERAGE LINE SPEED SORTED BY 5-KNOT INTERVALS

	Number of Lines				
Speed, knots	Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
0-5	0	1	8	9	0
6-10	2	2	11	15	1
11-15	4	4	14	22	0
16-20	4	7	25	36	3
21-25	6	6	8	20	4
26-30	8	8	11	27	5
31-35	7	5	7	19	7
36-40	3	4	9	16	3
41-45	0	7	2	9	3
46-50	2	3	1	6	0
51-55	2	1	3	6	4
56-60	2	0	2	4	2
≥ 61	0	3	4	7	2
Mean	29	32	24	27	36
Median	28	30	20	24	34
Greatest	56	72	68	72	70
Least	8	0	0	0	8

The median speed for the right ends of lines was 30 knots as compared to 32 knots for the left ends. The end points of each line were described as the left and right ends with respect to the direction from which the line was moving. For instance, if a north-south oriented line is moving from the west, the left end of the line is to the north and the right end is to the south. Due to the erratic nature of growth and dissipation of the echoes on the ends of lines, the median speeds for the end points were higher than for the center point and, also, were less representative of the line speed. However, the end point speeds do give some indication of the magnitude of change occurring in these line portions. An average speed of 102 knots was the highest recorded for an end point, whereas 72 knots was the highest average speed recorded for the center points (Table 3).

Dimensions of lines. The length of each line was defined as that distance between the left and right end points expressed in nautical miles. The median line length, based on the average lengths of the 196 lines, was 88 miles, and the longest average length of an individual line was 243 miles. The frequency of average line lengths sorted by 20-mile intervals is shown in Table 4. Sixty-three per cent of the lines had average lengths ranging between 50 and 100 miles, and 12 per cent had lengths greater than 150 miles.

The width of a line was a mean value determined from three measurements of the distance across the minor axis made at the center and near the end points. From the mean line-width measurements, determined every 30 minutes during the duration of a line, an average width was calculated for each line. The median line width, based on the average widths of the 196 lines, was 7 miles. As shown in Table 5, the greatest average width found for any line was 37 miles and the narrowest was 3 miles. Seventy-five per cent of all lines had average widths in the 3- to 10-mile range, and only 10 per cent of the lines had average widths greater than 16 miles.

TABLE 4

AVERAGE LINE LENGTHS SORTED BT 20-MILE INTERVALS

	Number of Lines				
Length, nautical miles	Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
50-70	8	9	34	51	1
71-90	9	12	28	49	3
91-110	6	8	16	30	10
111-130	4	8	10	22	5
131-150	7	5	8	20	3
151-170	3	4	4	11	2
171-190	1	3	1	5	4
191-210	0	2	1	3	0
211-230	2	0	1	3	3
≥ 231	0	0	2	2	3
Mean	110	108	94	101	142
Median	96	96	83	88	125
Greatest	221	203	243	243	243
Least	60	51	49	49	70

TABLE 5

AVERAGE LINE WIDTHS SORTED BY 4-MILE INTERVALS

Width, nautical miles	Number of Lines: Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
0- 4	6	6	32	44	1
4.1- 8	11	18	43	72	10
8.1-12	12	15	19	46	10
12.1-16	6	5	4	15	10
16.1-20	1	5	4	10	3
20.1-24	0	1	2	3	0
24.1-28	2	1	0	3	0
≥ 28.1	2	0	1	3	0
Mean	11	10	8	9	11
Median	9	9	6	7	9
Greatest	37	26	33	37	20
Least	3	3	3	3	4

Temporal changes in growth. Changes in growth during the duration of each line were classified according to three tendencies: increase, decrease, and neutrals These tendencies in growth were determined by changes in the number of echoes and in line dimensions. Because lines had different durations, which makes comparisons of temporal growth change difficult, the duration of each line was divided into quarter periods and growth tendencies were determined for each quarter. In this manner, growth tendencies of lines with different durations could be compared. In Table 6, the number of tendencies recorded in each quarter, expressed as a per cent of the 196 lines, is listed. The dominating tendency during the first quarter period was for increase. In the second period, the three growth tendencies had similar frequencies although neutral was slightly greater. In the third and fourth quarters, the tendency for decrease prevailed, with greater frequency in the fourth quarter than in the third.

TABLE 6

COMPARISON OF GROWTH TENDENCIES IN EACH QUARTER PERIOD OF LINE DURATION EXPRESSED AS A PER CENT OF ALL 196 LINES

Growth tendency	Quarter Periods: First	Second	Third	Fourth
Increase (I)	58	32	26	10
Neutral (N)	21	37	28	19
Decrease (D)	21	31	46	71
Growth tendency coded in descending order of frequency	IND	NID	DNI	DNI

Duration in time. The duration in time of each line's appearance on the scope was computed, A median value of two hours for line duration was obtained. The accuracy for which the actual duration of a line can be computed from a radar presentation is questionable because the radar limitations, especially range-height losses, strongly affect duration statistics. However, the findings may have some application for the radar meteorologist using the CPS-9 or similar radar equipment.

The longest duration found for a line was 15 hours, and the shortest duration was 0.5 hour (Table 7). Byers[5] found that 37 radar lines in Ohio during the summer had durations varying from 2 to 11 hours. The percentage of the total lines occurring in l/2-hour intervals is shown in Table 7. Seventy-four per cent of the 196 lines had durations of 3 hours or less, and only 10 per cent had durations greater than 5 hours.

TABLE 7

DURATION OF LINES SORTED INTO l/2-HOUR INTERVALS WITH NUMBER PER INTERVAL EXPRESSED AS A PER GENT OF TOTAL LINES

	Number of Lines				
Duration, in hours	Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
0.5-1.0	10	17	35	26	0
1.1-1.5	19	10	26	20	3
1.6-2.0	10	14	11	12	12
2.1-2.5	15	12	2	7	6
2.6-3.0	8	8	10	9	9
3.1-3.5	12	6	3	5	6
3.6-4.0	8	4	3	4	22
4.1-4.5	5	10	3	5	12
4.6-5.0	0	4	1	2	0
5.1-5.5	2	4	1	2	6
5.6-6.0	2	2	2	2	6
6.1-6.5	2	0	1	1	6
6.6-7.0	0	4	0	1	6
$\geq$ 7.1	7	5	2	4	6
Total lines	40	51	105	196	34
Mean	3.2	3.4	2.1	2.6	4.3
Median	2.5	2.5	1.4	2.0	4.0
Longest	9.0	15.0	7.8	15.0	8.0
Shortest	1.0	1.0	0.5	0.5	1.5

Time of occurrence. A study was made of the hours of line formation, or times of first scope appearance, and the periods of the day in which lines were present. Certain data limitations, including the preferred radar operational period of 0700 to 2300 CST, affect results pertaining to time of occurrence. However, since the radar-indicated inception and dissipation of all the 196 lines were recorded on the scope, the results concerning time of line formation should be useful, if the results for hourly increments in the 0700 to 2300 CST period (Table 8) are compared with each other. However, operations in the 1800 to 2300 CST period were not as frequent as in the 0700 to 1800 CST period, making results for these five nocturnal hours after 1800 CST somewhat biased.

As shown in Table 8, the preferred hour of line formation, based on radar detection, for all 196 lines was 1200 to 1300 CST, which agrees with other findings.(8) However, lines formed with almost equal frequency in every hour of the period from 0700 to 1800 CST. The preferred 2-hour and 3-hour periods for line formation were 1200 to 1400 CST and 1200 to 1500 CST, respectively.

Occurrence of lines during the day was examined by dividing the day into 6-hour periods, beginning with 0601 to 1200 CST, and then expressing the frequency of lines in each period. The analyses did not include the period of 0001 to 0600 CST because of the lack of data for this period. Since several lines occurred in more than one of the three periods, a total of 265 appearances were recorded for the 196 lines. In the period from 1201 to 1800 CST, 49 per cent of these appearances occurred, whereas 27 per cent were recorded from 0601 to 1200 GST, and 24 per cent in the period from 1801 to 2400 CST. Because there were fewer hours of operation in the 1801 to 2400 GST period, results for this period may not be as reliable as those for the earlier two periods.

TABLE 8

TIME OF LINE FORMATION IN THE 0600 TO 2300 CST PERIOD
EXPRESSED AS A PER CENT OF TOTAL LINES

Hour ending (CST)	Clockwise pivoting	Counter-clockwise pivoting	Non-pivoting	Total	Lines with severe weather
07	0	0	2	1	6
08	5	16	5	7	3
09	12	8	5	7	3
10	0	12	8	8	3
11	13	4	7	8	6
12	10	4	7	7	12
13	15	13	6	10	17
14	3	4	11	8	6
15	10	8	8	8	6
16	8	13	7	9	11
17	2	4	10	8	6
18	10	8	7	8	9
19	10	0	4	4	0
20	0	4	4	2	3
21	2	0	5	3	3
22	0	0	2	1	3
23	0	2	2	1	3
Maximum 1-hour period	12-13	07-08	13-14	12-13	12-13
Maximum 2-hour period	11-13	07-09	13-15	12-14	11-13
Maximum 3-hour period	10-13	07-10	13-16	12-15	11-14

Daily and monthly line frequencies. Using the 320 lines that were photographed in the 11-month period, various daily and monthly line frequencies were investigated. The results are shown in Table 9. Forty-one per cent of the 264 operational days had lines, and this frequency was lowest in winter and highest in summer. Only 8 per cent of the February days had lines compared to 86 per cent in July. An average of 5 lines per month was obtained for January and February compared to 62 and 88 lines, respectively, in June and July. July with 5 per day had the highest average number of lines on days with lines, and March ranked second with an average of 4 per day. April and June averaged 3 lines per day on days with lines, and the remaining months averaged between 1 and 2 lines per day with lines. The maximum number of lines on one day was 16 in July, although March, April, June, and October each had days with 8 or more lines. The relatively low number of

TABLE 9

MONTHLY LIKE FEEQUENCY DATA

	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
No. of days radar operation	22	7	25	20	21	27	24	24	21	26	26	21
No. of days with lines	3	3	14	8	7	4	2	5	11	14	20	18
Per cent of operational days with lines	14	43	56	40	33	15	8	21	52	54	77	86
Lines per month	5	5	37	15	13	6	4	19	32	34	62	88
Average number lines on days with lines	2-	2-	3-	2	2	2-	2	4	3	2+	3	5
Maximum number of lines on one day	3	2	8	3	3	2	3	7	8	5	12	16

lines in August and September were a result of very low rainfall in Illinois during operational periods. These findings, although not an accurate climatological representation of such statistics, do provide a relative measure of these frequencies.

Location of line centerso Location of line centers was recorded as to azimuth and range from the radar station. The azimuth locations of the center points were classified by occurrence in the eight 45-degree sectors of the compass (Fig,, 3). If the center moved through more than one sector, an occurrence was recorded for each sector through which the center passed. Line centers occurred most frequently in the sector from 90 degrees to 135 degrees, although relatively large frequencies were recorded in all the sectors from 315 degrees clockwise to 180 degrees.

The range data were described as an average distance during the line duration. Average center locations ranged from 5 to 198 miles. The median range based on the average ranges of the 196 lines was 88 miles.

Location of line formations. The location of line centers when the lines were first detected on the scope was investigated to ascertain the areal distribution of these locations,, A frequency analysis of the number of lines appearing in each 30-degree sector surrounding the radar set is shown in Table 10. This table reveals that there was very little significant difference by azimuth in the number of line formations, although the greatest frequency of formations occurred in the quadrant from southeast to southwest of the radar station. A slight secondary maximum

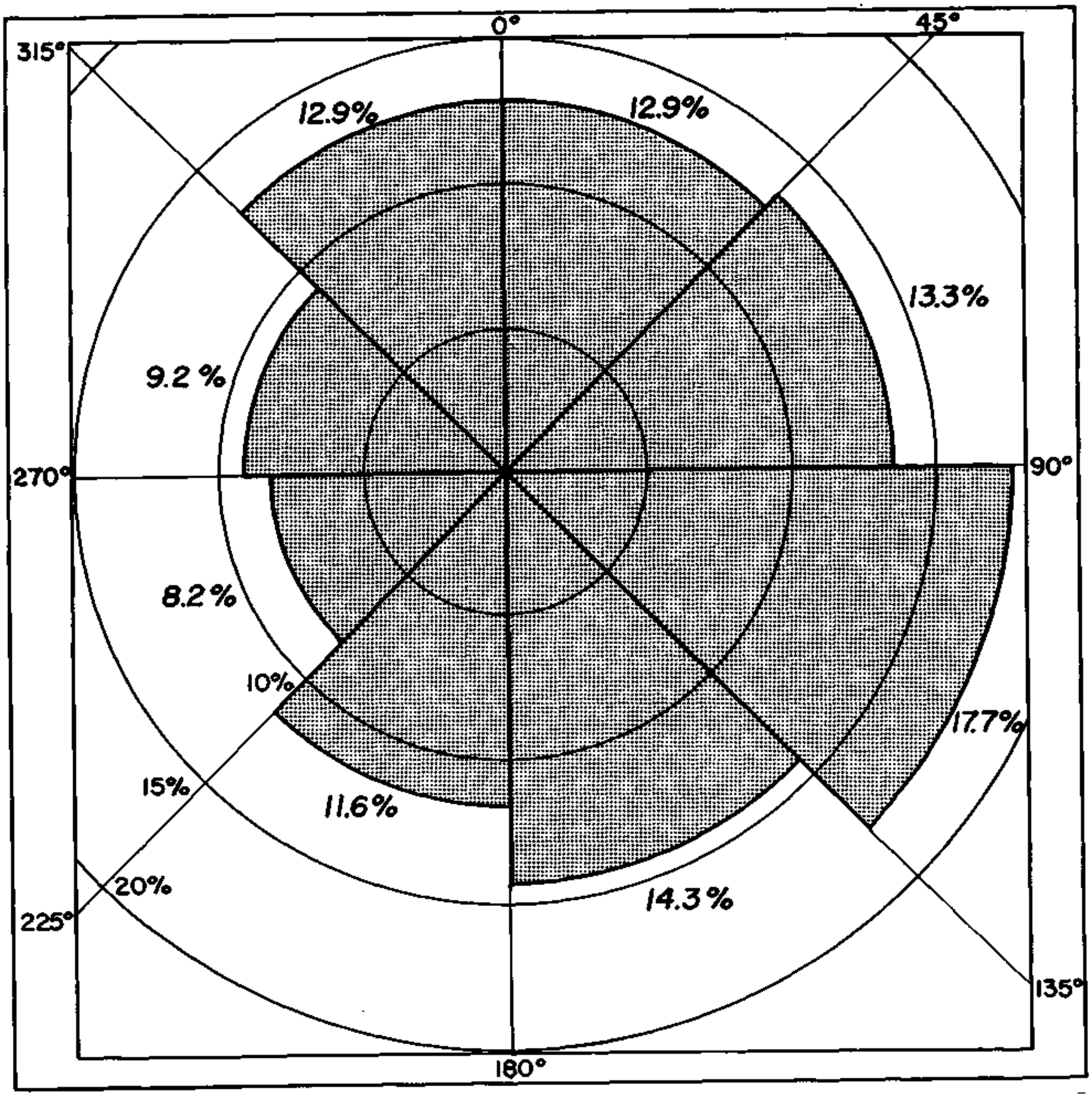


FIG. 3 FREQUENCY OF LOCATION OF LINE CENTERS, CPS-9. FREQUENCY IN EACH 45° SECTOR EXPRESSED AS A PERCENT OF TOTAL OCCURRENCES.

occurred in the two western-most 30-degree sectors. Line formations were somewhat less frequent to the northwest and northeast of the radar station.

In order to make a more detailed inspection of the formation locations by azimuths, a similar analysis was made of the first detection based on 10-degree azimuth sectors. This examination revealed that five 10-degree sectors had frequencies of line formations ranging from two to three times more than could be expected in 10-degree arcs if the formations had been normally distributed in azimuth around the radar set. These five sectors were 100 to 109 degrees, 129 to 138 degrees, 147 to 156 degrees, 205 to 214 degrees, and 246 to 255 degrees with 12, 13, 14, 12, and 11 line formations in each, respectively. Thirty-three per cent of the 196 lines formed in the 50 degrees included in these five sectors; whereas, if normally distributed, only 14 per cent of the lines could have been expected to occur in any 50 degrees of azimuth,, One 4-degree sector, 106 to 109 degrees, had 8 line formations occurring in it.

As a further effort to determine locations where line formations on the scope were most frequent, the ranges to the center points of the lines detected in these five 10-degree sectors were examined to ascertain whether a grouping by range occurred. Five of the 12 lines in the sector from 100 to 109 degrees originated at ranges from 68 to 80 miles, and this area is marked "a" on Figure 4. Seven of the 14 lines in the sector from 147 to 156 degrees formed in the 12-mile range distance of 93 to 105 miles,

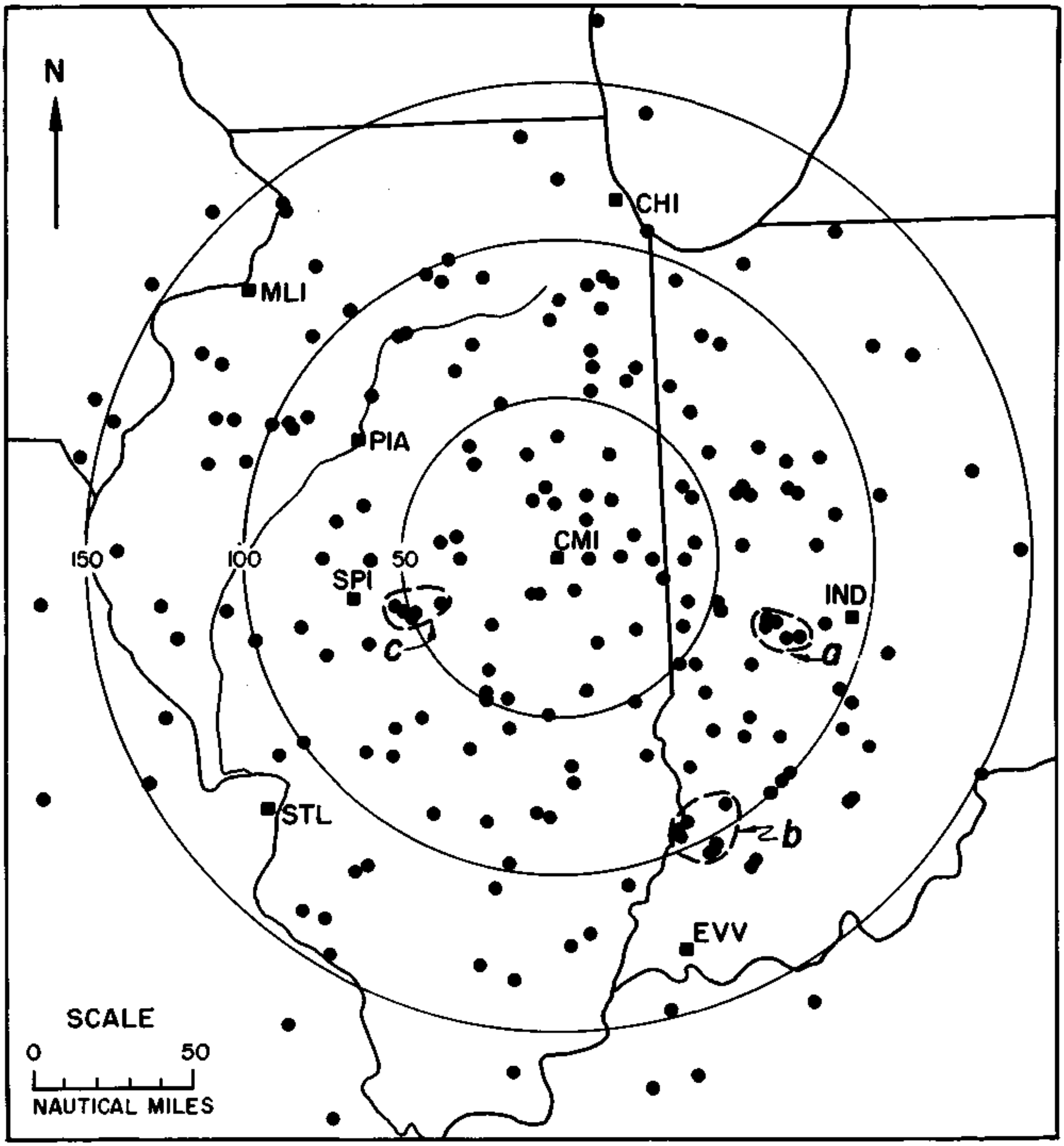


FIG. 4 LOCATION OF CENTER POINTS OF LINES AT TIME OF FIRST APPEARANCE, CPS-9

marked as area "b" on Figure 4. The third region of rather frequent occurrences was found in the sector from 246 to 255 degrees with 5 of the 11 lines in that sector initiating at ranges from 40 to 54 miles (area "c", Fig. 4). The greater frequency of formations in areas a, b, and c does not appear to be statistically significant and no outstanding topographic features are located in these areas.

The median and average range and the distribution of ranges by 25-mile intervals for lines forming in each or the 30-degree sectors, are presented in Table 10. Examination of these data reveals a preference for lines to form in the 25-mile range ring from 76 to 100 miles, and almost 46 per cent of the 196 lines initiated in the 50-mile range ring from 50 to 100 miles. This is in keeping with previous findings on GPS-9 rainfall detectability.[8] Table 10 data also indicate that the preferred 50-mile range ring for lines forming in the sectors from 331 degrees clockwise to 120 degrees was the 50- to 100-mile range. Lines forming in the south-southeast and west most frequently formed in the 50-mile range ring from 76 to 125 miles. In general, it appears that lines to the south and the west were detected at ranges somewhat greater than lines in other azimuth locations.

However, if these range ring frequencies are normalized for the area in each ring, the ring of greatest formation frequency is not 75 to 100 miles. Data in the last column of Table 10 reveals that formations were most frequent in the 0-25 range ring where 5 formations per 1000 square miles was the frequency. The formation frequency diminished with range when normalized by area. Beyond the 100-mile range the number of formations per unit area decreases repidly, almost 50 per cent fewer in the first ring beyond 100 miles. Assuming a random distribution of line formations in space, this sudden decrease in line formations beyond 100 miles may imply that the early stages of line formation are frequently not detected because the initial line echoes of these long ranges are below the radar beam. Such an implication would indicate that possibly one-half of the line echoes in their initial stages have tops at elevations of 11,000 feet or less.

Direction of movement exhibited by lines forming in each of the 30-degree sectors was investigated also to ascertain whether lines forming in different areas tended to have directions of movement exhibiting significant variations from the median of 265 degrees. The directions of line movement after formation were classified by occurrence in the eight 45-degree sectors of the compass. This examination revealed that the lines forming in the three sectors from 1 to 90 degrees exhibited the greatest variety in directions of movement. For instance, the 17 lines forming in the sector of 61 to 90 degrees had line movements in all eight 45-degree sectors. The preferred 90-degree sector of line directions of movement for ten of the 30-degree sectors of formation was 225 to 315 degrees. However, for the lines forming in the 30-degree sectors of 211 to 240 degrees and 241 to 270 degrees the preferred 90-degree sector of line movements was from 131 to 270 degrees, a somewhat more southerly direction than movements for lines forming in the other ten 30-degree sectors.

TABLE 10

LOCATION OF LINE FORMATION

	1°-30°	31°-60°	61°-90°	91°-120°	121°-150°	151°-180°	181°-210°	211°-240°	241°-270°	271°-300°	301°-330°	331°-360°	Totals	Number per 1000 square miles
Azimuth														
Number of lines	14	12	17	17	20	18	20	13	19	18	12	16	196	
Range in 30-degree sectors														
Average, miles	80	78	77	73	92	96	98	86	91	105	104	70		
Median, miles	74	74	76	70	97	100	89	87	80	108	104	74		
Occurrence in range rings, miles														
0-25	1	2	1	0	0	1	1	1	0	0	0	3	10	5.0
26-50	1	1	2	4	1	2	4	2	4	2	2	2	27	4.6
51-75	5	3	5	6	4	3	2	2	5	2	0	4	41	4.2
76-100	5	2	6	4	8	3	5	3	3	4	3	4	50	3.7
101-125	0	2	1	2	6	6	1	3	2	5	3	2	33	1.9
126-150	1	2	2	1	0	1	4	2	3	3	2	1	22	1.0
151-175	1	0	0	0	1	1	2	0	1	2	2	0	10	0.4
176-200	0	0	0	0	0	1	1	0	1	0	0	0	3	0.1
Greatest range	170	135	146	150	162	178	192	138	180	155	155	133		
Least range	22	15	25	34	33	12	14	14	31	33	40	16		

Comparison of Lines with Different Types of Rotation

Pivoting lines, the 91 with more than 10 degrees rotation, were compared with nonpivoting lines, the 105 with 10 degrees or less rotation during line duration. The median values for certain

TABLE 11

COMPARISON OP MEDIAN VALUES FOR LINE PROPERTIES OP PIVOTING AND NONPIVOTING LINES

Type of movement	Speed, knots	Width, miles	Length, miles	Duration, hours	Orientation, degrees	Direction of movement, degrees
Pivoting	29	9	96	2.5	258	265
Nonpivoting	20	6	83	1.4	254	250

properties are shown in Table 11. The pivoting lines were larger (Tables 4, 5), persisted longer (Table 7), and moved faster (Table 3) than the nonpivoting lines. The median orientations were much the same, but the preferred directions of movement differed by 15 degrees. The pivoting lines had 21 degrees of rotation on the average during their duration whereas the nonpivoting lines had a median rotation of 3 degrees (Table 1). The median rotation per hour for the pivoting lines was 8 degrees, but the nonpivoting lines rotated at a rate of 2 degrees per hour (Table 2). The nonpivoting lines more frequently formed *in* the 1300 to 1600 CST period (Table 8), whereas the pivoting lines formed more frequently in the 1000 to 1300 CST period. Almost 90 per cent of the pivoting lines were associated with thunderstorms, or could be considered as squall lines, but only 70 per cent of the nonpivoting lines were associated with thunderstorms. The growth tendencies of the two types of lines were dissimilar in the second quarter when the predominating growth tendency was neutral for the pivoting lines, but was decrease for the nonpivoting lines. Many of these differences suggest that the pivoting lines were associated with more intense and vigorous synoptic systems than were the nonpivoting lines.

Comparisons also were made between pivoting lines which rotated in opposite directions. Many of the properties of the two types of lines were similar, including the median orientation, width (Table 5), length (Table 4), duration (Table 7), speed (Table 3), rate of rotation (Table 2), growth tendencies, and preferred quarter period for occurrence. The major differences were associated with direction of movement and time of line formation (Table 8). The lines rotating in a clockwise direction moved most frequently from 265 degrees whereas the counterclockwise rotating lines moved most frequently from 325 degrees. As shown in Table 8, the preferred 3-hour period for line development for the clockwise lines was 1000 to 1300 CST as compared to 0700 to 1000 CST for the counterclockwise lines.

Lines Associated with Severe Weather

Damages produced by tornadoes, hail, rain, wind, and lightning[9] were found to be associated with 34 of the 196 lines. Median values of properties of lines associated with these forms of severe weather were compared with those derived from the 196 lines, hereafter referred to as the climatological lines. Inspection of Table 12 reveals that on the average, lines with severe weather persisted twice as long, pivoted more, and were wider and longer than the climatological lines. More detailed comparisons of the differences can be obtained by inspection of the data in

TABLE 12

COMPARISON OF LIKE DATA FOR LINES ASSOCIATED WITH SEVERE WEATHER WITH DATA FROM CLIMATOLOGICAL LINES

Medians

Lines	Duration, hours	Length, miles	Width, miles	Orien-tation, degrees	Pivot/hour, degrees	Speed, knots	Direction of movement, degrees
Climato-logical	2.0	88	7	255	4	24	265
weather	4.0	125	9	240	5	34	265

Tables 1 through 8. The lines with severe weather also frequently assumed more north-south orientations and moved faster than did the climatological lines. Seventy per cent of the severe weather lines were pivoting lines as compared to 46 per cent of the climatological lines. Furthermore, all severe weather lines were squall lines but only 80 per cent of the climatological lines were classified as squall lines. Median values of the lines associated with severe weather were used to synthesize the scope portrayal of these lines (Fig. 5). The preferred 3-hour period of formation for the severe weather lines was 1100 to 1400 CST (Table 8) as compared to the 1200 to 1500 CST period for the climatological lines. The severe weather lines also had a greater tendency for increases in growth to persist into the second and third quarters of duration. As shown in Figure 5, the centers of the severe weather lines most frequently were located in the 315- to 360-degree sector as compared to the 90- to 135-degree sector for the climatological lines

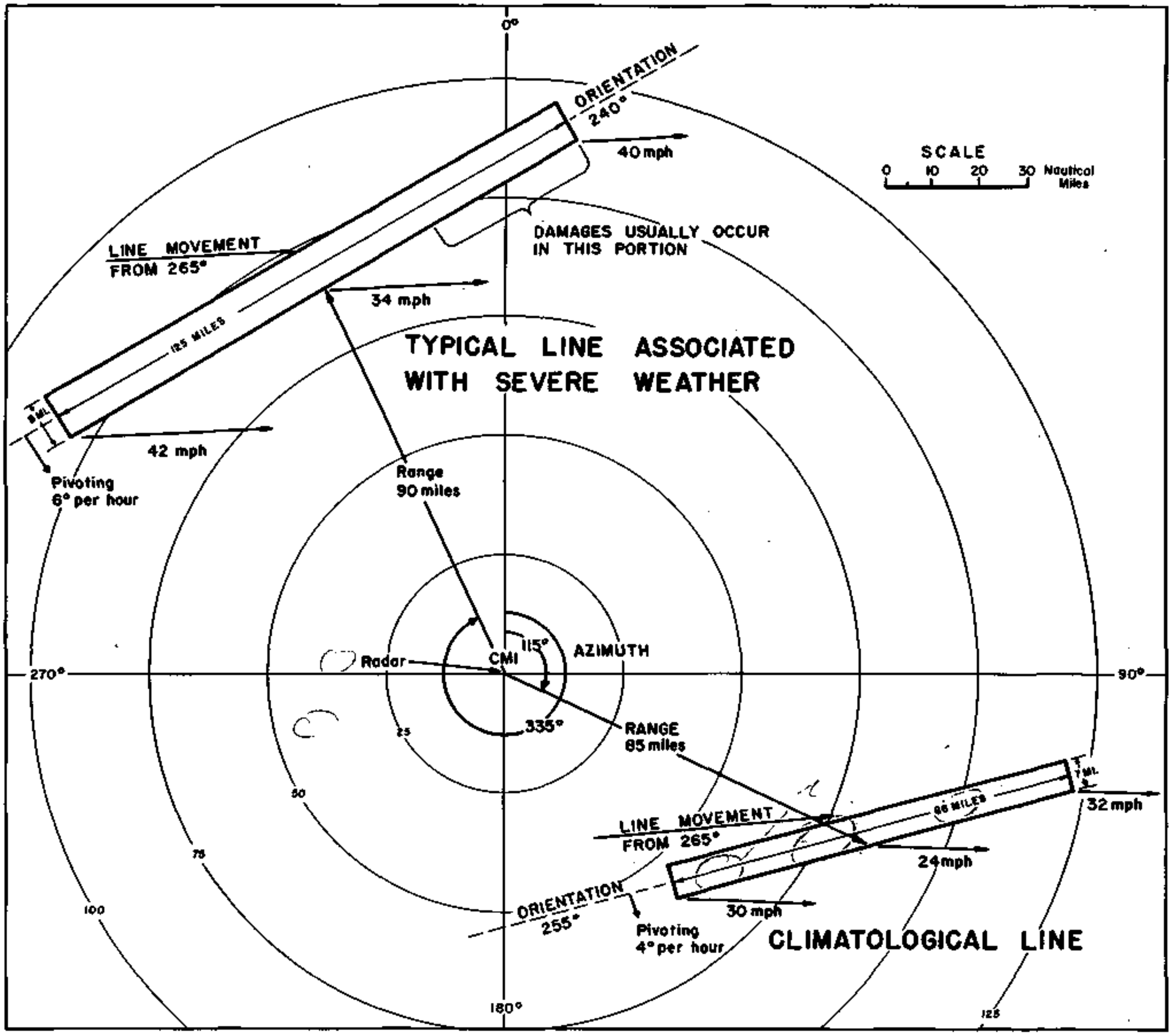


FIG. 5 PICTORIAL ILLUSTRATION OF TYPICAL RADAR-DEPICTED LINES AS SYNTHESIZED FROM MEDIAN MEASUREMENTS, CPS-9

(Fig. 3).

With 70 per cent of the lines, damages occurred in the second and third quarters of line duration. Only infrequently, three per cent of the time, did the damages occur in the fourth quarter of line duration. In moat of the 34 lines, certain abrupt changes were found in the portions nearest to the area of surface damage when the severe weather was occurring. These changes appear in Table 13. With 71 per cent of the lines, damages were associated in time with increases in line speed in that portion of the line near the damage area, and 42 per cent of the lines exhibited increases in pivoting in that portion of the line near the damage area at the time of damage. Increases in line size occurred with 18 per cent of the lines, and damages associated with two lines resulted from their intersection. With four lines, no changes in the line could be detected near the damage area at the time of damage.

TABLE 13

SUDDEN CHANGES IN PORTIONS OF LINES NEAR THE DAMAGE AREA AT THE TIME OF DAMAGE PRODUCED BY SEVERE WEATHER

	Type of Changes							
	No change	Inter-section of lines	Increase pivot	Increase speed	Increase size	Increase in speed and pivot	Increase in speed and size	Increase in speed, size and pivoting
Number of lines	4	2	3	9	1	10	4	1
Per cent of total severe weather lines	12	5	9	26	3	30	12	3

The location of the severe weather in respect to position along the major axis of the line also was investigated, and the results are presented in Table 14. With 27 lines, the damages occurred in the left one-third portion of the line (Fig. 5), and nine lines had damages in the right one-third portion of the line. With three lines, damages were occurring along the entire length.

TABLE 14

LOCATION OF DAMAGE ALONG MAJOR AXIS OF LINES ASSOCIATED WITH SEVERE WEATHER

	Along entire line	Left end	Left and center	Center	Right and center	Right end
Number of lines	3	19	5	1	1	5
Per cent of total lines with severe weather	9	55	15	3	3	15

APS-15 CLIMATOLOGICAL STUDY

Introduction

A climatological investigation was also made of lines measured with the low-powered, APS-15, 3-cm radar set. The purpose was to compare the characteristics of lines observed with CPS-9 and APS-15 radar sets. The same type of measurements were made for the data from both sets.

Description of Data

Data used in this study consisted of photographs of the APS-15 PPI on maximum receiver sensitivity. The maximum receiver sensitivity remained fairly constant during the periods of data collection with an average sensitivity of -89 dbm, only 4 db less than the CPS-9. There was a 32 db difference in the overall performance characteristics between the CPS-9' and APS-15 radars. The PPI photographs used were those with range settings of 100 and 150 nautical miles. The shorter operating ranges of the APS-15 as compared to the CPS-9 affects the statistics concerning range, duration, and line length, and consequently makes comparisons of these data difficult. However, comparisons are presented to evaluate the operational characteristics of the two sets. All distance measurements used in this study, as in the previous study, are in nautical miles.

The data used were collected during the May through September period of 1953 and the March through September period of 1954. Operations of the radar were not continuous during these two periods, so the available data do not provide a complete sampling of all lines occurring in these two periods. From the available photographic data, 99 lines were detected either wholly or partially on the scope photographs. The photographic records of 36 lines were incomplete due to operational schedules, and data for these lines were discarded from the analysis. The study was based upon data from the 63 lines with complete records. The number of complete lines per month was 2 in March, 2 in April, 21 in May, 21 in June, 6 in July, 8 in August, and 3 in Septemver. During these summer months, when relatively low numbers of lines were detected, precipitation was generally below normal.

Climatological Findings

Orientation, The median orientation of the 63 lines was 252 degrees, and 62 per cent of the lines had orientations ranging from 200 to 260 degrees. The number of orientations occurring in each 20-degree sector in the arc from 180 degrees clockwise to 360 degrees was computed, and the results are depicted in Figure 6. The preferred 20-degree sector was 240 to 260 degrees. Comparison of the orientation data in Figures 1 and 6 indicates that similar distributions of orientations were obtained from both the CPS-9 and APS-15.

Direction of movement. A frequency distribution of line movements was obtained for the twelve 30-degree sectors of the compass, and the number of lines in each sector was expressed as a per cent of the total lines (Fig, 7). This figure reveals that almost 43 per cent of the lines moved from azimuths ranging from

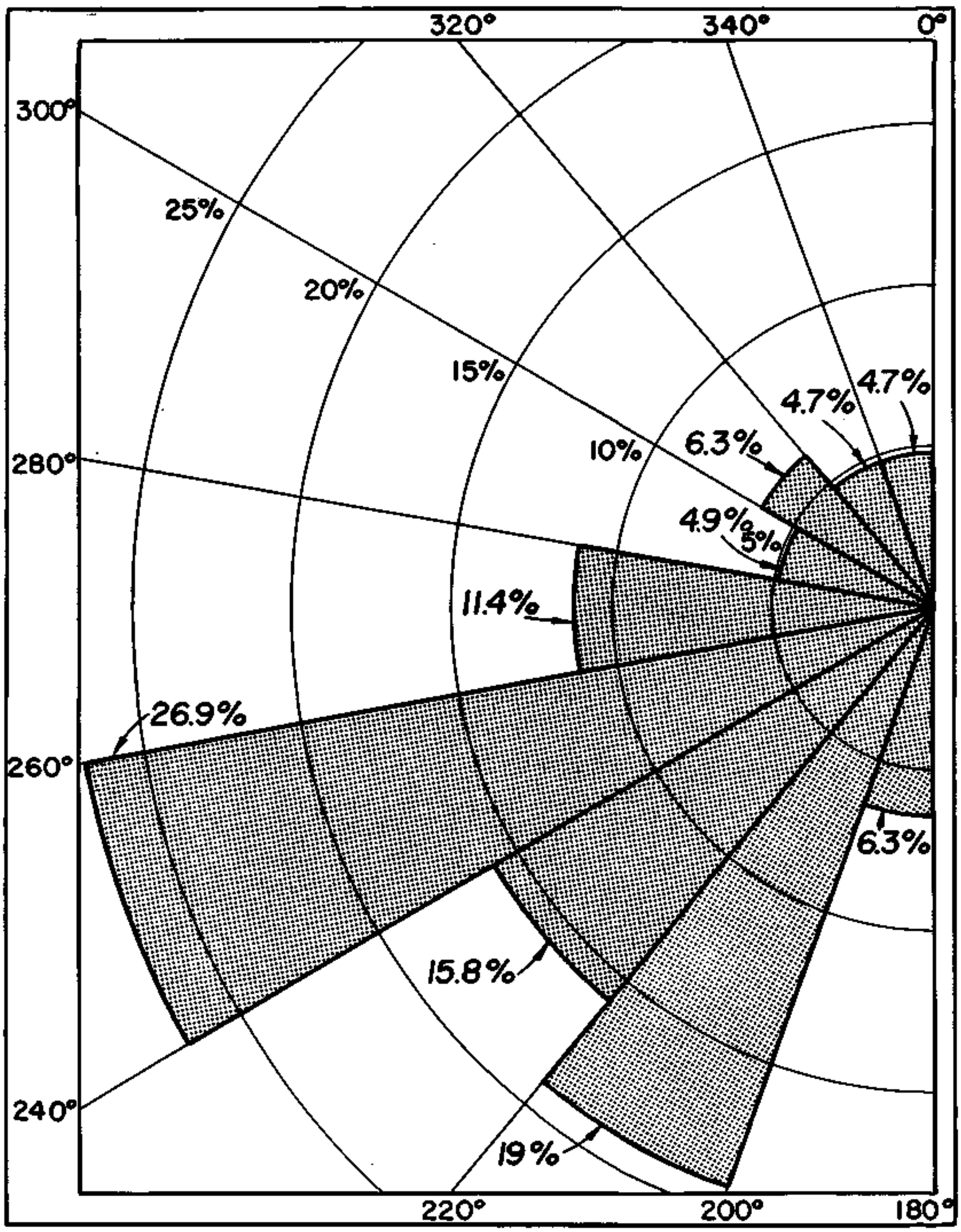


FIG. 6 FREQUENCY OF AZIMUTH POSITION OF LINE ORIENTATIONS, APS-15. FREQUENCY IN EACH 20° SECTOR EXPRESSED AS A PERCENT OF TOTAL LINES.

240 to 300 degrees. The median direction of movement was 275 degrees.

Type of movement. Fifty-five of the 63 lines, or 87 per cent, had some measurable amount of pivoting. The mean amount of rotation during the scope duration of the lines was 12 degrees which compares favorably with the mean of 13 degrees (Table 1) for the CPS-9 lines. On the average, the APS-15 lines pivoted at the rate of 6 degrees per hour, the equivalent of the rate for GPS-9 lines. Of the 27 lines pivoting more than 10 degrees during their duration, 17 rotated in a clockwise direction and the remaining 10 rotated in a counterclockwise direction.

Speed of movement. The mean of the average speeds of the center points of the 63 lines was 26 knots. The maximum average speed observed for any line was 74 knots. These line-speed statistics compare favorably with those determined for the 196 CPS-9 lines (Table 3).

Dimensions of lines. The mean line length based on the average line lengths of the 63 lines was 74 miles as compared to the 101-mile mean (Table 4) for the CPS-9 lines. The longest average length found for any line was 134 miles which was considerably less than the. maximum of 243 miles for a CPS-9 line (Table 4)0

The mean of the average widths of the 63 lines was 7 miles as compared to 9 miles for the CPS-9 lines (Table 5). The widest CPS-9 line was 37 nautical miles, almost twice the maximum average width for the widest APS-15 line which was 19 miles.

Temporal changes in growth. Changes in growth during the

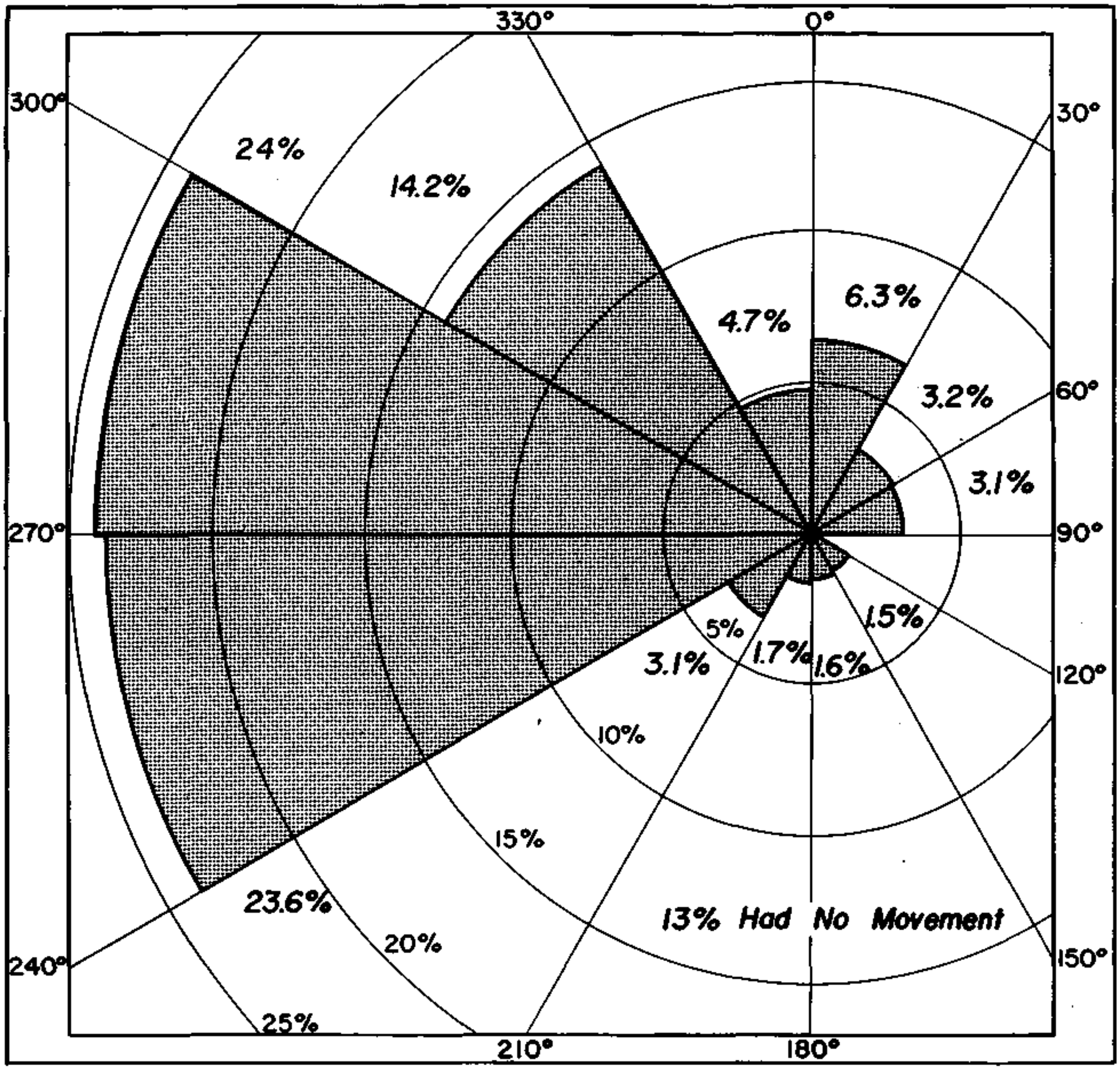


FIG. 7 FREQUENCY OF DIRECTION OF LINE MOVEMENTS, APS-15. FREQUENCY IN EACH 30° SECTOR EXPRESSED AS A PERCENT OF TOTAL LINES.

four quarters of scope duration of each of the 63 lines were classified in a manner identical to that used for the CPS-9 lines. In the first, third, and fourth quarters, tendencies displayed by the APS-15 lines agreed with those tendencies displayed by the CPS-9 lines (Table 6)0 In the second quarter, the APS-15 lines had a prevailing tendency for decrease rather than neutral as did the CPS-9 lines. On the average, the GPS-9 will detect a line at an earlier stage of development than will the APS-15, and this may account for this difference noted in growth tendencieso

Duration in time. The average duration of APS-15 lines was 2.1 hours, and the longest duration for one line was 9.1 hours. In order to examine the effect of line speed on duration, the durations of all lines moving slower than the average speed (26 knots) were averaged and compared with the average durations of those lines moving faster than the average speed. No significant difference was found between the average durations of the slow and fast-moving lines, indicating that line speed had little effect on line duration.

Time of occurrence. Time of line formation, or first detection on the scope, was analyzed for the 63 lines,, The preferred 1-hour period for line formation was 1600 to 1700 CST. In this hour, 18 per cent of the 63 lines first appeared,, The 2-hour period with the maximum number of line formations was 1500 to 1700 CST. Comparison of these results with those appearing in Table 8 indicates that the APS-15 lines had a tendency for detection later in the afternoon than those appearing on the CPS-9 radar set.

The occurrence of lines during the day was examined by dividing the day into 6-hour periods, beginning with the period from 0601 to 1200 CST, and then expressing the frequency of line occurrences in each of the three 6-hour periods from 0601 to 2400 GST. In the 1201 to l800 period, 45 per cent of the total line occurrences were recorded, as compared to 49 per cent in this period for the CPS-9 lines. The second highest frequency for a 6-hour period occurred in the 1801 to 2400 period which had 33 per cent of the APS-15 line occurrences. In this same period, the CPS-9 occurrence frequency was 24 per cent of the total occurrences. However, APS-15 and CPS-9 results for the 1801 to 2400 CST period are biased to some extent because operations were not as frequent in this period as during the two prior 6-hour periods.

Location of line centers. The azimuth locations of the line center points were classified by occurrence in the eight 45-degree sectors of the compass. If the center moved through more than one sector, an occurrence was recorded for each sector through which the center passed. By this method of recording center locations, it was found that the 63 lines produced 93 occurrences of centers in the $ sectors. As shown in Figure 8, the center points had preferred locations to the northwest and southeast of the radar station, and were found most frequently in the 45-degree sector from 135 to 180 degrees, as compared to a preference in the 90- to 135-degree sector for the CPS-9 lines. It is interesting that both studies revealed the most frequent location of line centers to be southeast of the radar station.

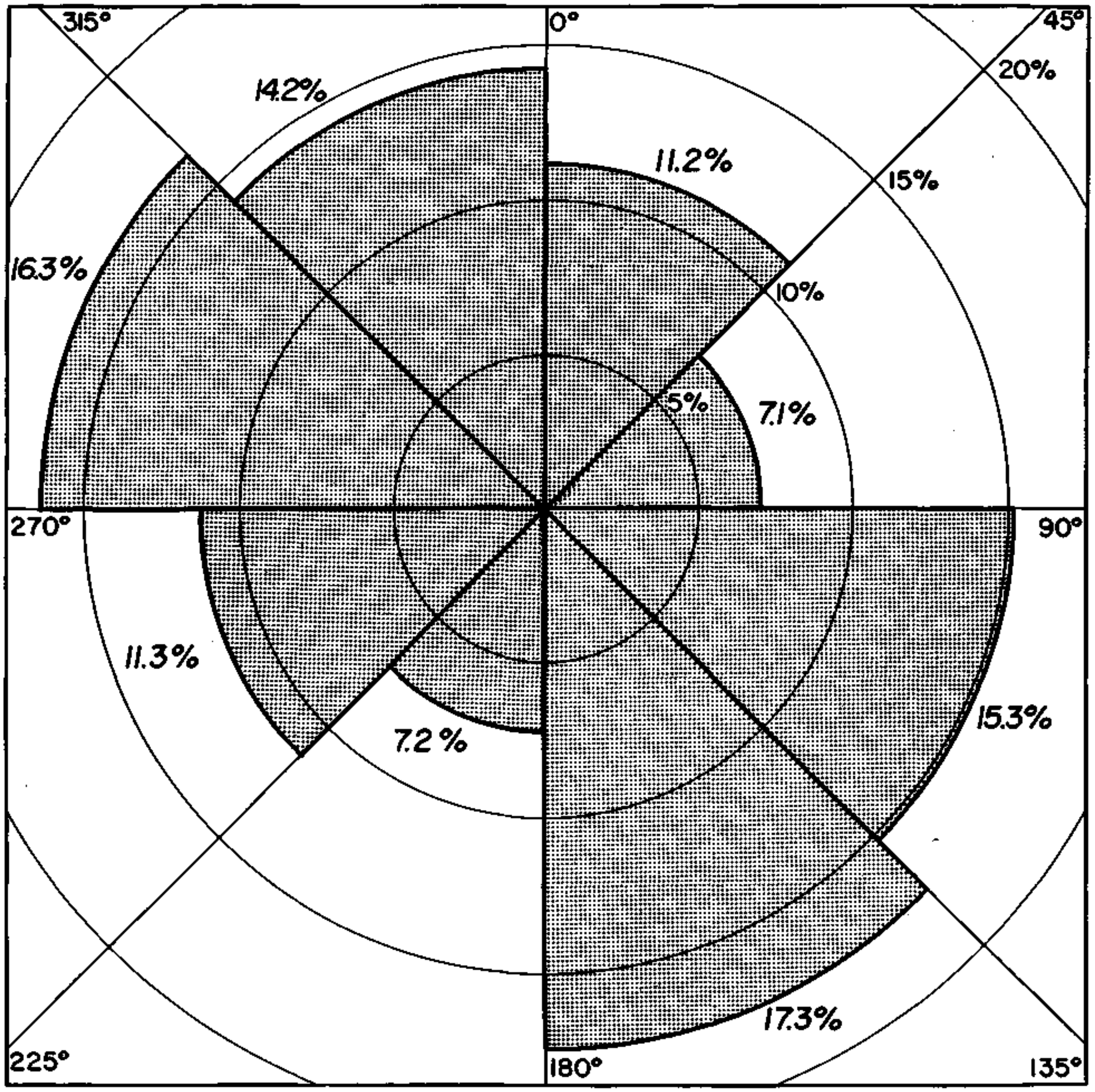


FIG. 8 FREQUENCY OF LOCATION OF LINE CENTERS. APS-15. FREQUENCY IN EACH 45° SECTOR EXPRESSED AS A PERCENT OF TOTAL OCCURRENCES.

The average locations of center points of the 63 lines were found to lie anywhere from 5 miles in range out to 94 miles. The mean range, based on the average ranges for all center points, was 48 miles as compared to 88 miles for the CPS-9 lines. This range difference is largely a result of the difference in detectability of the two sets.

Comparison of APS-15 and CPS-9 Radar Line Characteristics

A comparison of line characteristics derived from the two radar sets was made to ascertain if any differences existed and if so, of what magnitude. Results for certain selected characteristics are presented in Table 15• The lines from the different radar sets had very similar average and median values for the four characteristics previously classified as climatologically reliable (orientation, direction of movement, type of movement, and speed). No significant differences appear in Table 15 for these characteristics.

The differences between the APS-15 and CPS-9 radar lines appeared in those line characteristics considered less reliably measured by radar, including duration, time of occurrence, time of formation, dimensions, and growth tendencies. As expected, the high-powered CPS-9 set with its greater range detection depicted lines as much larger and with greater duration than those depicted by the low-powered set.

TABLE 15

COMPARISON OF DATA DERIVED FROM
CPS-9 AND APS-15 PRECIPITATION LINES

Line characteristics	CPS-9	APS-15
Median orientation	255°	252°
Preferred 20° sector of orientation	220°-240°	240°-260°
Median direction of movement	265°	275°
Preferred 30° sector of movement	250°-280°	270°-300°
Average amount of pivoting (all lines)	13°	12°
Per cent of total lines pivoting 1° or more	96	89
Per cent of total lines pivoting 11 or more	46	43
Average amount of pivoting per hour	6°	6°
Per cent of pivoting lines (>10) rotating in clockwise direction	44	62
Average speed, knots	27	26
Greatest average speed of single line, knots	72	74
Average length, miles	101	74
Average width, miles	9	7
Greatest average length of single line, miles	243	134
Greatest average width of single line, miles	37	19
Prevalent growth tendencies in four quarters, first to fourth	INDD	IDDD
Average line duration, hours	2.6	2.1
Greatest duration for single line, hours	15.0	9.l
Maximum 3-hour period of line formation (CST)	1200-1500	1400-1700

CPS-9 HEAVY RAINFALL STUDY

Introduction

Using data from a CPS-9 radar and from recording rain gages in Illinois, a study was made of the characteristics of precipitation lines and zones that result in heavy rainfall in Illinois, This study is part of an extensive investigation of the meteorology of Illinois storms which was undertaken to obtain information relative to the characteristics and causes of severe rainstorms in the state.

In the first phase of the study, analysis was made of storms within 150 miles of the radar station which had precipitation lines and which produced hourly amounts exceeding one inch during periods of radar observations. A total of 33 storm days during 1955-53 satisfied these criteria. Of the 108 lines observed on the 33 storm days, 54 were responsible for hourly rainfall amounts exceeding one inch.

Attention was given to the orientation, shape, and motion of the lines, and a comparison was made with the distribution of these parameters in the climatological sample of radar-depicted lines. The presence of intersecting lines and the variability in orientation and movement of lines on each of the 38 days were investigated, A synoptic typing of these storms was made also.

In the second phase of the study, the 10 most severe rainstorms that have occurred in Illinois during the past 10 years were investigated. Primary emphasis was placed upon shape and motion in these storms and upon how precipitation lines assumed an important role in the development of these storms.

Data Used

Radar data used in the study consisted of 35-mm photographs of the PPI presentation on the CPS-9. Rain gage data included hourly rainfall tabulations from 85 U. S. Weather Bureau recording rain gage stations in Illinois and from four concentrated networks containing 94 recording gages operated by the Illinois State Water Survey. In selecting the cases for the first phase of the study, a tabulation was made of all storms in which one or more rain gages recorded hourly amounts exceeding one inch. Reference was then made to radar logs and film records to determine the number of cases for which adequate radar data were available.

The procedure used in the climatological study df precipitation lines was followed in tabulating the radar line data for analysis. Measurements of the various parameters were made at 30-minute intervals. In addition, echo contour maps for 30-minute intervals and isohyetal maps for 1-hour intervals were drawn for each of the 38 storm days on base maps which included Illinois and portions of the adjacent states.

Measurements of radar echo lines were made mostly from photographs taken on maximum receiver sensitivity settings. Reduced gain was used occasionally to clarify merging or intersecting lines. No attempt was made to interpret the gain-step photographs in terms of rainfall intensity, since previous experience had indicated that such calculations are not practical with 3-cm radar.

Measurements were made of the length, width, orientation, speed, direction of movement, rotation, and growth tendencies of each line and the location of the line with respect to the radar station. The accuracy of measurement and the limitations in interpretation are the same as listed earlier in the discussion of the climatological study. Orientation, movement, and location can be determined usually with satisfactory accuracy; but line dimensions, duration of lines, and growth tendencies are dependent upon radar characteristics and useful only when compared with similar measurements in the climatological sample made with the same radar set.

Characteristics of Heavy Rainfall Lines

Orientation. An average orientation was obtained for each line. Table 16 shows the distribution of orientations for the 54 lines which produced observed hourly rainfall amounts in excess of one inch. The median orientation was 245 degrees, and the most frequent orientations were 230 to 239 degrees and 240 to 249 degrees, each with 15 per cent of the total lines. Using all of the 108 rainfall lines on the 38 heavy rainfall days, the median and the most frequent orientations were the same as for the 54 lines. In the climatological study of CPS-9 lines, the median was 255 degrees and the most frequent occurrence was in the range from 221 to 240 degrees. It is of interest to note that Huff and Semonin[11] found that the median orientation of rainfall patterns in 262 storms, each of which produced four inches or more of rainfall in Illinois, was 265 degrees and the most frequent orientations were from 241 to 260 degrees. Studies of the Illinois Water Survey indicate that squall lines or zones were associated with all of the severe rainstorms of appreciable areal extent in Illinois in the past 10 years.

TABLE 16

DISTRIBUTION OF ORIENTATIONS OF LINES PRODUCING HEAVY RAINFALL INTENSITIES

Sector, degrees	Per cent of all lines	Sector, degrees	Per cent of all lines
180-39	2	270-79	2
190-99	0	280-89	4
200-09	11	290-99	7
210-19	11	300-09	5
220-29	4	310-19	4
230-39	15	320-29	0
240-49	15	330-39	4
250-59	4	340-49	0
260-69	12	350-59	0

Variations in orientations of lines occurring on same day, A study was made of the variation of orientation of lines on storm days. On 28 of the 38 storm days investigated, two or more lines were tracked during the period of radar observations. The distribution of the maximum differences in the average orientation of lines on these 28 days is shown in Table 17. The table shows that 60 per cent of the days with multiple precipitation lines had a variation in orientation between lines that exceeded 45 degrees. Results suggest that relatively strong convergence or wind shear of meso-scale proportions frequently occurs on days with heavy rainfall intensities, in order to produce lines of radically different orientations within such relatively short distances. Lines with large differences in orientation generally exhibited converging motion with west-east oriented lines moving northward or southward, and north-south or NE-SW oriented lines moving eastward. Merging or intersection of lines frequently resulted from this converging motion,

TABLE 17

VARIATION IN ORIENTATIONS OF LINES

Maximum difference, degrees	Number of cases	Per cent of cases	Cumulative per cent of cases
76-90	7	25	25
61-75	6	21	46
46-60	4	14	60
31-45	7	25	85
16-30	3	11	96
≤ 15	1	14	100

Type of movement. Previous investigators(12) have found cases of severe weather associated with rotating and intersecting precipitation lines. An investigation of the rotating characteristics of the 54 heavy rainfall lines indicated a median value of 9 degrees per hour with the most frequent value 6 to 10 degrees per hour, considerably greater than the climatological sample which showed a median of 4 degrees per hour. The distribution of rotations shown in Table 18 indicates that anticyclonic rotation is more frequent than cyclonic.

Intersecting or merging lines were observed on 24 per cent of the days with heavy rainfall lines, indicating that such occurrences are frequently associated with heavy rainfall intensities.

TABLE 18

ROTATION OF LINES

Degrees per hour	Cyclonic	Anticyclonic	Total
	Number of Cases		
0-2	4	6	10
3-5	2	8	10
6-10	7	11	18
11-15	5	3	8
16-20	1	2	3
21-30	1	2	3
Over 30	1	1	2

Rotation exceeded 10 degrees per hour in 30 per cent of the lines causing heavy rainfall. No analysis has been made as yet to evaluate the separate effects of meso-scale wind convergence and vertical development of echoes on the rotation of squall lines.

Direction of movement. The direction of movement of precipitation lines on the 38 storm days was expressed as the azimuth from which the lines moved. The most frequent direction of movement was in the 30-degree sector from 266 to 295 degrees, followed closely by the sector from 236 to 265 degrees. No radical departures were found from the climatological distribution which showed most frequent occurrences from 251 to 280 degrees.

Speed of movement and growth tendencies. The median speed of the lines which produced heavy rainfall intensities was found to be 39 knots, compared to 24 knots for the climatological sample. Although the increase of 63 per cent in the median speed of the heavy rainfall lines appears quite significant, it may be due, partially at least, to the tendency for more pronounced and longer growth periods in these storms. With the climatological sample it was found that line growth tended to predominate during the first fourth of the radar history of lines, the second quarter was neutral, and in the last half of their history dissipation was predominant. With the heavy rainfall lines, growth was predominant in the third quarter, and dissipation most frequently occurred during the last quarter.

Dimensions of lines and duration in time. The median length of the heavy rainfall lines was found to be 160 miles and the median width 11 miles, compared to a median length of 88 miles and median width of 7 miles with the climatological sample. Thus, storms producing heavy rainfall intensities appear to be considerably larger than the average convection system. As expected, considering the greater size of the heavy rainfall convection systems, the median radar duration of these lines was found to be 3.2 hours compared to 2.0 hours with the climatological sample.

Synoptic weather types with lines. An investigation was made of the type of synoptic weather systems associated with radar-depicted lines in both the climatological and heavy rainfall samples. Synoptic types were based upon daily weather maps prepared by the U. S. Weather Bureau. Results are shown in Table 19. Reference to this table shows that cold and stationary frontal systems were most frequently associated with the heavy rainfall days, accounting for 60 per cent of the cases. In the climatological sample, which was composed of 73 days in 1955, air mass storms were more promineht and, in conjunction with cold fronts, accounted for 53 per cent of the 73 days. Low center passages in Table 19 include both wave centers with fronts and closed lows without fronts, but the majority were wave-center passages.

TABLE 19

ASSOCIATION OF SQUALL LINES WITH SYNOPTIC SYSTEMS

Synoptic type	Climatological Sample		Heavy Rainfall Sample	
	Number of days	Per cent of days	Number of days	Per cent of days
Cold front	21	29	14	37
Warm front	5	7	6	16
Stationary front	9	12	9	23
Occluded front	7	10	2	5
Air mass storms	18	24	6	16
Low center passage	10	14		13
Upper trough or front	3	4	0	0

Analysis of 10 Severe Rainstorms

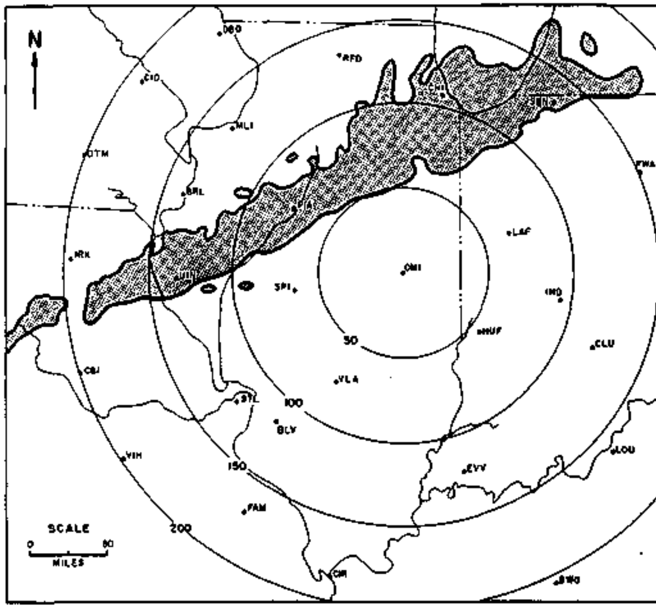
Applying radar data in conjunction with recording rain gage and synoptic weather data, a study was made of the characteristics of the 10 most severe rainstorms in Illinois during the past 10 years. These storms were not included in the previous study of heavy, short-duration, rainfall intensities. Total storm amounts excee'ded 10 inches in 8 of these storms. All occurred with quasi-stationary squall zones through which several precipitation lines passed. In this paper, discussion is restricted to the maximum 12-hour rainfall period in each storm.

Typical radar and hourly rain gage data used in studying the characteristics of rainstorms are illustrated in Figures 9-12. The two types of data complement each other and provide information on location, shape, orientation, areal extent, movement of lines, and intensity of rainfall. In Figures 11 and 12 for October 6, 1955, attenuation has distorted the radar presentation somewhat; but combined with the rain gage presentation, it provides a detailed picture of the situation. The rain gage data were used for estimation of the intensity distribution.

The orientation of storms with respect to basins is an important factor in flood forecasting and in hydraulic design problems; consequently, an analysis was made of storm orientations. The median orientation of the rainfall pattern in the 10 storms was found to be 265 degrees, and 9 storms had orientations between 250 and 290 degrees. The precipitation lines associated with the storms had a median orientation of 255 degrees and a range from 230 to 300 degrees. In most of the storms, the difference in orientation between rainfall patterns and precipitation lines was less than 20 degrees.

In general, the precipitation lines decelerated rapidly upon reaching the quasi-stationary squall zone of heavy rainfall, and accelerated and decreased in intensity upon leaving the zone. The median speed of lines through the heavy rainfall zones was 8 knots, and the speed was less than 20 knots in all 10 storms (Table 20). The median speed of lines outside the squall zone was 20 knots.

Intersecting and/or merging lines were observed in the heavy rainfall zone with five of the severe rainstorms, and appeared to be associated with the initiation of heavy rainfall at the start



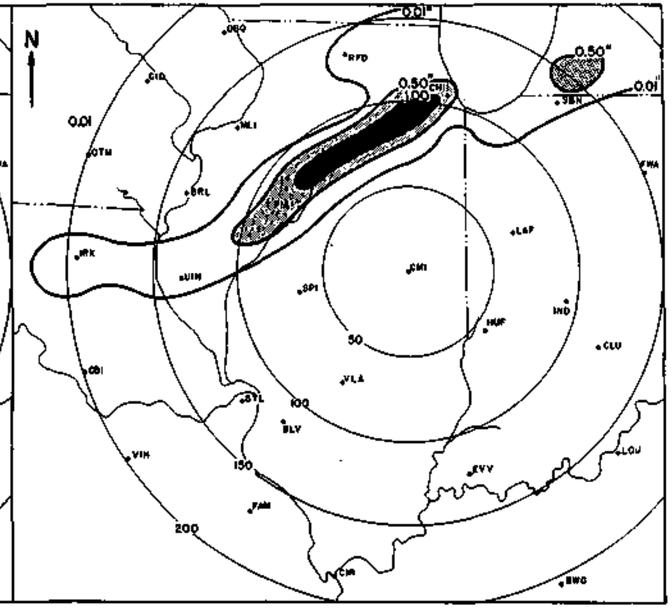
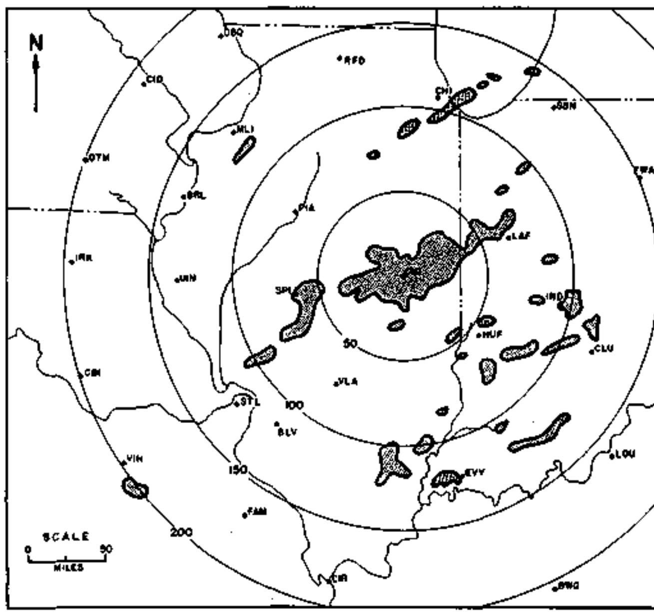


FIG. 9 RADAR PATTERN , 1800-1900 CST, JULY 2, 1958 FIG.IO ISOHYETAL PATTERN , 1800-1900 CST, JULY 2,1958



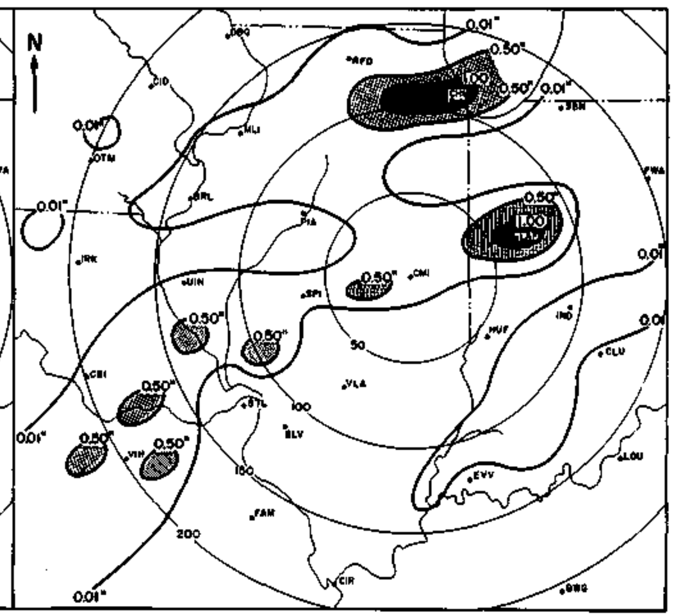


FIG. 11 RADAR PATTERN , 1500-1600 CST, OCT 6,1955 FIG. 12 ISOHYETAL PATTERN, 1500-1600 CST, OCT. 6,1955

TABLE 20

LINE MOVEMENT VERSUS WIND COMPONENT NORMAL TO LINE

		Component speed, knots			
Date	Avg. line speed, knots	850 mb	700 mb	500 mb	850-500 mean
7/8/51	6	-7	-6	25	5
7/18/52	6	0	5	11	5
10/9/54	5	10	5	8	8
5/26/56	7	16	9	-4	6
5/21/57	8	-18	-23	-21	-21
6/14/57	8	-7	8	9	4
6/27/57	7	8	6	13	9
7/12/57	16	-18	-10	14	-4
7/14/58	13	13	11	18	14
8/16/59	11	3	11	13	10

of three storms and with the occurrence of the heaviest rainfall burst in the other two storms. Distinct waves on precipitation lines were observed in three storms. Appreciable rotation of lines was noted in three cases.

On 8 of the 10 storm days, precipitation lines with orientations varying by 45 degrees or more were observed within 200 miles of the radar station. These lines displayed converging motion, with generally west-east oriented lines moving in a northerly or southerly direction, whereas other lines with north-south or NE-SW orientations moved in an easterly direction. An outstanding example of this motion was displayed prior to and during the storm of June 27-28, 1957. Movements of lines during a 6-hour period of heavy rainfall are shown in Figure 13. The frequent observations of lines with radically different orientations and movements on

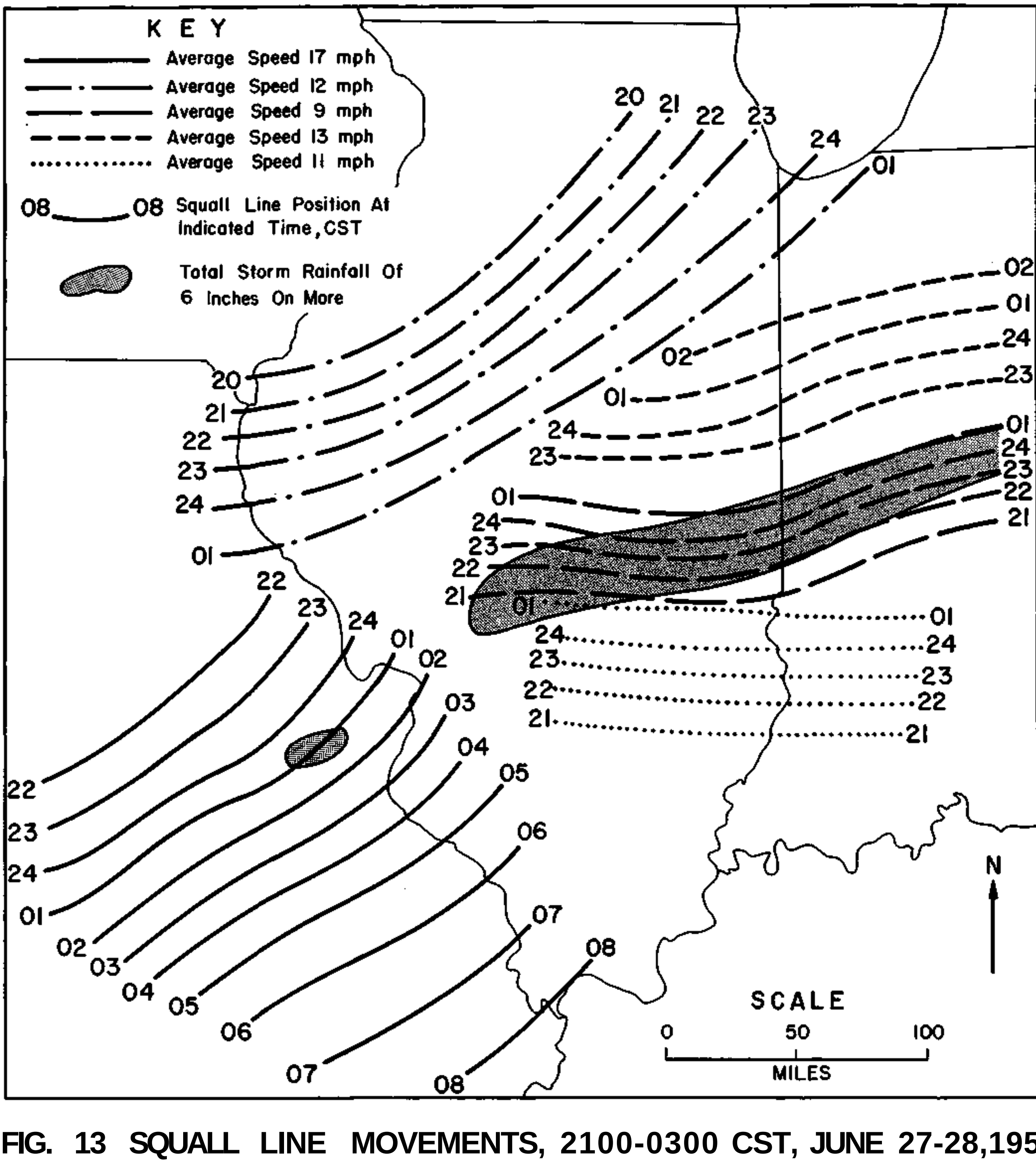


FIG. 13 SQUALL LINE MOVEMENTS, 2100-0300 CST, JUNE 27-28,1957

days with severe rainstorms and on days with lines which produced heavy, short-period intensities, discussed earlier, suggest the use of such radar observations as an aid in forecasting heavy rainfall.

Investigation of the wind field associated with the quasi-stationary squall zones in the 10 storms indicated that the component of the 850 mb to 500 mb wind normal to the line correlated well with the precipitation line movements through the zone in the majority of the cases but poorly in a few cases. Results of this investigation are shown in Table 20. Negative components represent a wind force opposing the observed motion of the lines. Of the individual levels, the 700-mb level had the best correlation with the line movements.

Analysis of wind direction and speed in the 10 storms showed a median of 260 degrees, 31 knots for the mean wind in the layer from 850 to 500 mb, with individual storms varying between 210 and 230 degrees, 20 to 45 knots. Median values at 850, 700, and 500 mb, respectively, were 245 degrees, 31 knots; 255 degrees, 31 knots; and 270 degrees, 31 knots.

SUMMARY AND CONCLUSIONS

Climatological investigations of 196 precipitation lines appearing on the CPS-9 radar PPI and of 63 precipitation lines appearing on the APS-15 radar PPI indicate that the results obtained for four line characteristics are climatologically reliable. Although the precipitation lines exhibited a wide range of orientation, direction of movement, speed, and type of movement, it appears that these four characteristics can be accurately measured by radar, and the derived results are reliable climatologically.

The preferred orientation of 255 degrees for the CPS-9 lines compared favorably with a preferred orientation of 252 degrees for the APS-15 lines. The preferred directions of movement of lines on the two radars were much the same with a direction of 265 degrees for the CPS-9 lines as compared to the 275 degrees for the APS-15 lines. Close agreement was found in the results for average line speeds with a mean of 27 knots for the CPS-9 lines as compared to 26 knots for the APS-15 lines. The fourth line characteristic considered to be reliable is the type of movement, which refers to the rotation of the major axis of lines. During the scope duration of the CPS-9 lines, 13 degrees pivoting occurred on the average as compared to 12 degrees for the APS-15 lines. The average amount of line pivoting per hour was 6 degrees for both the CPS-9 lines and APS-15 lines.

Other line characteristics which were not as reliably measured by radar included line dimensions, duration, time of occurrence, area of occurrence, and growth tendencies. However, orders of magnitude could be determined for these characteristics. The findings from the two radars concerning these characteristics differed as might be expected because of the power and range differences of the CPS-9 and APS-15 radar sets. For instance, the mean length of the CPS-9 lines was 101 miles as compared to 74 miles for the APS-15 lines, and the mean width was 9 miles for the CPS-9 lines as compared to 7 miles for the APS-15 lines.

The growth tendencies displayed by the CPS-9 lines during their scope durations indicated that during the first quarter, lines were increasing, and during the second quarter lines were experiencing very little change or were in a neutral growth condition. During the third and fourth quarters, the lines were decreasing in both size and number of echoes. However, during the second quarter of duration the APS-15 lines had a preferred tendency for decrease rather than neutral. CPS-9 lines had an average duration of 2.6 hours as compared to 2.1 hours for the APS-15 lines. Another difference between the line data from the two radars was the preferred hours of line formation or initial scope appearance. The first detection of APS-15 lines tended to be more frequently in the middle and late afternoon as compared to early afternoon for the CPS-9 lines.

A detailed investigation of line rotation based upon the 196 CPS-9 lines revealed that 46 per cent of all lines rotated more than 10 degrees during their duration and that 96 per cent of all these lines had some measurable amount of rotation. The pivoting lines, those with more than 10 degrees rotation, were more frequently associated with thunderstorms than were the nonpivoting lines. The nonpivoting lines also had a tendency for decrease in the second quarter of duration as opposed to neutral for the pivoting lines. The nonpivoting lines most frequently formed in the period from 1300 to 1600 CST whereas the pivoting lines formed most frequently in the period from 1000 to 1300 CST. Many of these differences between pivoting and nonpivoting lines suggested that the pivoting lines were associated with more intense and vigorous synoptic systems than were the nonpivoting lines.

Comparison of the pivoting lines which rotated in opposite directions revealed that, in general, the properties of the lines rotating in different directions were similar. The major differences between lines rotating in opposite directions concerned direction of line movement and time of line formation.

Investigation of the radar characteristics displayed by 34 lines associated with severe weather indicated that certain characteristics of these lines differed considerably from the climatological lines. In general, the lines associated with severe weather had a much longer scope duration, and were considerably larger than the climatological lines. These severe weather lines also moved considerably faster, but did have similar directions of movement. The severe weather lines tended to have orientations which were more north-south than were orientations of the climatological lines. Seventy per cent of the severe weather lines pivoted more than 10 degrees compared to 46 per cent of the climatological lines.

The damages associated with the 34 severe weather lines occurred frequently during the second and third quarters of line duration. Close examination of lines at the time of damage revealed that often sudden changes in speed, pivoting, and line size occurred near the area of damage, and that frequently the damages occurred along the left one-third portion of the lines. It would appear, based on this relatively small sample of severe weather lines, that the lines which produced severe weather were associated with much stronger convective systems than were most of the climatological lines, and that scope appearances of these severe weather lines might be sufficiently different from those of the climatological lines to permit a radar observer to identify and forecast lines which had a potential for development of severe weather.

A study of radar-depicted precipitation lines associated with hourly rainfall amounts of one inch or more indicated that the heavy rainfall lines, in general, were longer, wider, exhibited longer duration of growth, greater speed, and more rotation than those in a comparable climatological sample that included all types of precipitation lines. Large deviations in orientation and motion between individual lines were characteristic of the heavy rainfall days, and this tendency may prove useful in short-period forecasting of heavy rainfall.

In an investigation of the 10 most severe rainstorms in Illinois during the period 1950-59, it was found that these storms occur in a quasi-stationary squall zone through which a series of precipitation lines pass. These lines tend to decelerate rapidly upon reaching the quasi-stationary squall zone, and accelerate and decrease in intensity upon leaving the zone. Intersecting and/or merging lines are frequently associated with the initiation of the storm or with the occurrence of the heaviest rainfall burst during the storm. Distinct waves on the precipitation lines are sometimes observed, and appreciable rotation of lines occurs in some storms. In most cases, the precipitation line movement through the squall zone is in good agreement with the component of the wind normal to the line in the layer from 850 mb to 500 mb. The lines tend to become nearly parallel with the upper winds as they reach the squall zone, which results in the surface rainfall pattern having an orientation similar to the mean upper wind. Median orientation of the surface rainfall pattern for the 10 storms was 265 degrees, and the median value of the wind in the layer from 850 to 500 mb was 260 degrees.

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